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MAGNETO-OPTIC EFFECTS @ 1.15 MICROMETER
IN $\text{Gd}_{0.5}\text{Y}_{2.5}\text{Ga}_1$ IRON GARNET THIN FILM
WAVEGUIDES

A. R. Reisinger, et al

IBM Thomas J. Watson Research Center

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13. ABSTRACT We report on the frequency response of the mode conversion process in our magneto-optic thin film waveguides. Experiments were carried out (a) by application of a magnetic field step pulse and (b) by rf excitation. The dynamical behavior of the magnetization was monitored simultaneously by optical detection and electromagnetic sensing. It was determined that the magnetic field required for switching increases with frequency. The implications of this property are discussed in terms of driving circuit design			

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MAGNETO-OPTIC EFFECTS @ 1.15 μm in $\text{Gd}_{.5}\text{Y}_{2.5}\text{Ga}_1$
IRON GARNET THIN FILM WAVEGUIDES

5th Quarterly Technical Report
(January 1 - March 31, 1974)

July, 1974

by

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INTRODUCTION

The previous quarterly technical report¹ described the observation of magnetization oscillations in our $(\text{Gd}_{0.5}\text{Y}_{2.5})(\text{Ga}_1\text{Fe}_4)\text{O}_{12}$ films. Electromagnetic detection by means of a balanced, half-turn pick-up loop susceptible to flux changes,² showed that the free oscillations ranged in frequency from ~ 200 to ~ 900 MHz depending on bias conditions and crystallographic orientation.¹

During the present reporting period, we have endeavored to determine if the above encouraging results could be translated into optical modulation in the same range of frequencies. Optical switching speed experiments were carried out under two different sets of conditions: (i) application of a step-pulse magnetic field and (ii) continuous excitation at increasing RF frequencies. The best results observed to date are a rise time of 60 nsec and a forced modulation at 25 MHz. These figures are not necessarily to be construed as the ultimate limits intrinsic to our films, but, rather, reflect the difficulty of designing a wideband driving circuit capable of generating, with moderate currents, the switching magnetic field of a few Oersteds required by the material available to us.

1. PULSED EXCITATION

The experiment was done on sample #851 which had a coercive field of 1.5 Oe measured at 60 Hz. The optical propagation direction was chosen at 45° with respect to the easy axis, since, as explained in our third quarterly report,³ this direction requires the least amount

of magnetic field to annihilate the stripe domains.³ A periodic permalloy pattern was positioned against the magneto-optic film in order to boost the mode conversion efficiency in a manner described in an earlier report.⁴ The resultant structure was then placed within a 50 Ω strip line, terminated by a 50 Ω matching load, as illustrated in Fig. 1. By comparing the optical modulation caused by a 60 Hz current flowing either in the strip line or in an external calibrated coil, it was determined experimentally that the strip line generated at that frequency a field of 0.5 Oe/Amp at the location of the sample. In order for the magneto-optic film to switch, it is necessary that the external longitudinal field change sign. We, therefore, adopted the procedure schematically illustrated in Fig. 2. A 60 Hz longitudinal field was applied by means of a set of external coils. A high power pulse generator, synchronized with the 60 Hz, launched into the strip line a current pulse timed to coincide with the onset of the off/on transition (Point A in Fig. 2-a). Stated differently, the fast pulse is used to "kick" the switching process "on" while the slow 60 Hz resets the film in the "off" configuration. An S-1 photomultiplier, with a rise time of ~ 2 nsec was used to detect the optical modulation. The signal was fed into an amplifier (Hewlett Packard 461, input impedance 50 Ω and bandwidth from 1 KC to 150 MHz) processed through a Boxcar integrator (PAR 160) and displayed on a storage oscilloscope (Tektronix 549) as shown in the diagram of Fig. 3.

The speed of the optical response was found to depend strongly on the amplitude of the magnetic field pulse. The results plotted in open circles in Fig. 4 show that the rise time decreased from about 10 μ sec at a current pulse of 1.2 Amp (the minimum required for switching) down to some 60 nsec for a maximum current of 10 Amps available from our pulse generator (5 kW peak power dissipated in the 50 Ω terminating load). The pulse width had no effect provided that it was longer than the rise time of the optical signal. The 60 nsec limit of the optical response shown in Fig. 4 can be accounted for by the fact that it is approximately the value of the rise time of the pulse itself.

We then used a pulse generator with a much faster rise time of 2 nsec (type SKL generator). The voltage amplitude was limited to 130 V, giving a peak current of 2.6 Amps. The result of the measurement is shown as a full circle in Fig. 4, where it can be seen to fall on the same curve as the other data points.

Notice also on Fig. 4 that over 2 orders of magnitude - the optical rise time seems to be approximately inversely proportional to the third power of the current pulse. An explanation for this rather puzzling observation will be offered in the next section.

Fig. 5 is a photograph of the optical signal obtained with a current pulse amplitude of 8 Amps. The picture is noteworthy because of the ringing, at a frequency of about 9 MHz, noticeable on the trailing edge of the optical response. Similar oscillations were recently reported by Moody et al⁵ who attributed them to domain wall motion. This

similarity raises some question as to whether the mechanism responsible for modulation might be wall motion rather than magnetization rotation. It can be argued that the periodic permalloy structure will inevitably give rise within the magneto-optic film to domains separated by 180° walls which may or may not remain immobile during the modulation process.

It was, therefore, felt necessary at this point to attempt to measure the intrinsic switching speed of a sample without any periodic permalloy structure. The approach chosen was to apply a RF modulating field of increasing frequency, and is the object of the next section.

II. RF MODULATION

In an earlier report⁶ we discussed mode conversion in our magneto-optic films when subjected to a homogeneous modulating field. Although the mode conversion efficiency is limited to typically less than 1%, we described how a detectable optical modulation at the frequency of the AC field could be observed by setting the analyzer at 45° with respect to the input polarization of the laser beam.⁶ The same technique was used here to determine the frequency response of our films in the absence of the permalloy structure.

In view of the relatively large currents (5 to 10 A) that were found to be required for switching, the specimen was placed in a short-circuited strip line. A pick-up loop of the type described in Ref. 1 was incorporated so as to be able to observe switching simultaneously by electro-

magnetic sensing and optical detection. The experimental configuration is shown in Fig. 6.

The impedance of the strip line was measured up to 20 MHz. The results, plotted in Fig. 7, show that the strip line can be well approximated - at least in that range of frequency - by the equivalent circuit shown in the inset. Essentially one deals with a pure resistor of $\sim 0.013 \Omega$ below 100 KC, whereas above 100 KC the strip line behaves like an inductor of $0.019 \mu\text{H}$.

Electro-magnetic sensing via the pick-up loop enabled us to determine that strip line current requirement for switching goes up with the frequency. In order to ascertain whether this is a true magnetic property of our films or if it is simply due to the fact that more and more current might be needed at higher frequencies to generate a given magnetic field, we placed in the strip line a one-turn loop perpendicular to the field lines and measured the flux change as a function of frequency. This test proved conclusively that the magnetic field/current calibration of the strip line was quite constant from DC to at least 500 KC. We conclude thus that it is indeed the coercive field of our films that increases with frequency. Fig. 8 shows this phenomenon for two representative samples. It can be seen that the coercive field is approximately proportional to the frequency raised to the power $1/3$. Consequently, an increase of the modulating field by a factor of 10 increases the frequency response by about 3 orders of magnitude. This statement is entirely consistent with our experimental finding described in the

previous section that the rise time of the optical signal was approximately inversely proportional to the third power of the switching current pulse (or equivalently of the magnetic field pulse). It follows that, in the range of our measurements, our samples display essentially the same frequency response with or without the periodic permalloy structure.

Driving the shorted strip line does not present much of a problem at audio frequencies since there exist commercially available oscillators and amplifiers with low input impedance. At RF frequencies, however, most equipment is designed for 50 Ω loads and can tolerate only a small fraction of reflected power, which raises the problem of impedance matching. Transformers appear to be impractical because cores with appropriate frequency characteristics are not readily available. We used instead a narrow-band, tunable LC matching network illustrated in Fig. 9. It is basically a parallel resonant circuit, one leg of which consists of a variable inductor L in series with the shorted strip line and the other is a variable capacitance C .

It is shown in the Appendix that L and C must be chosen so as to simultaneously obey the following two relations:

$$(L + L_s) C \omega^2 \approx 1 \quad (1)$$

$$(L + L_s)/C = R_s^* R_o \quad (2)$$

where Eq. (1) is the resonance condition and Eq. (2) insures impedance matching. The quantity R_s^* appearing in Eq. (2) is the resistance of the

strip line at RF frequency (taking into account the skin effect). Eliminating C between Eqs. (1) and (2), one obtains:

$$\omega = (R_s^* R_o)^{1/2} / (L + L_s) \quad (3)$$

It is clear from Eq. (3) that matching by this method can be achieved only up to a maximum frequency such that

$$\omega \leq \omega_{\max} = (R_s^* R_o)^{1/2} / L_s \quad (4)$$

when the inductance of the strip line itself is used to resonate the matching circuit. At RF frequencies, the current drawn by the strip line made of brass of thickness $a = 1.5$ mm and width $b = 6$ mm is concentrated near the surface of the conductor, within the skin depth δ .

The high frequency resistance R_s^* is then given in terms of the "DC" value R_s through the relation:

$$R_s^* / R_s = \left[(a^{-1} + b^{-1}) 2\delta \right]^{-1} \quad (5)$$

where

$$\delta = \sqrt{2 / \omega \mu_o \sigma}$$

Using a resistivity $\rho = \sigma^{-1} = 6.3 \times 10^{-8}$ ohm-m for brass,⁷ Eq. (5) yields $R_s^* / R_s \approx 22$ or $R_s^* \approx 0.25 \Omega$ around 20 MHz. Substitution of this last value together with $R_o = 50 \Omega$ and $L_s \approx 0.02 \mu\text{H}$ back into Eq. (4) gives a maximum frequency of 30 MHz.

Experimentally, the actual value of L_s was a little higher because of additional inductance associated with cables and connectors. The strip line was matched at 25 MHz when resonated with a capacitance of 1500 pF, giving a Q of about 10. Some modifications, indicated in Fig. 11, were made in the experimental set-up in order to avoid the 50 MHz bandwidth limitation of the Boxcar integrator. The optical signal was passed through a wideband amplifier (Avantek, 15 dB gain, 5 MHz to 300 MHz bandwidth) and fed into a Tektronix 661 Sampling Oscilloscope for partial integration and amplification. The output was then further processed through the Boxcar integrator and finally displayed on the storage scope as before. Fig. 11 shows the optical modulation at 25 MHz (top picture) together with the signal detected by the electromagnetic pick-up loop (bottom picture). Notice the high frequency ringing observed by electromagnetic sensing. These oscillations are believed to be another manifestation of the underdamped oscillatory behavior of the magnetization described in the previous quarterly report¹ as the oscillation frequency depends on the magnitude of a perpendicular DC magnetic field bias (see Fig. 12). The 900 MHz ringing reported previously corresponded to a DC bias of 150 Oe, whereas in this experiment, we were limited to a maximum of 20 Oe, which kept the oscillation frequency in the range of 200 to 400 MHz. So far we have been unable to see any evidence of optical modulation at these free oscillation frequencies. It should, of course, be kept in mind that the pick-up loop senses a flux change, i.e., a signal proportional to the frequency. It is conceivable that the actual

amplitude of the oscillatory behavior is too small to cause any detectable optical modulation (which is not proportional to the frequency) in spite of the fact that the electromagnetic signal is quite large due to the high frequency.

CONCLUSIONS

We have observed optical modulation in our garnet waveguides up to 25 MHz at this writing, although the electromagnetic signal is observable from 250 to 450 MHz with a DC bias of a few to 20 Oe (900 MHz oscillations have been reported previously with a stronger DC bias of 150 Oe). These oscillations at the natural resonance frequency are easily observable even with a half turn pick-up loop because the sensitivity of inductive detection is proportional to the frequency. Unfortunately, optical detection does not enjoy the same property.

In order to achieve optical modulation at higher frequencies, more power than is presently available from our generator has to be applied. The power requirement results from a combination of material properties and design considerations:

- (a) We have experimentally observed that the magnetic field needed to saturate the magnetization in our films increases with frequency. It is possible that films with completely in-plane magnetization may not suffer from this drawback.
- (b) The gap of the strip line used in our experiments was 1.75 mm in order to accommodate the physical size of a garnet film plus the periodic permalloy structure deposited on a separate

substrate. This limited the electric to magnetic conversion to about 0.5 Oe/Amp. This figure can be increased by reducing the gap.

- (c) A wideband matching network is required to compensate for the inductance of the strip line and simultaneously match the low resistance strip line to the 50 Ω output impedance of the power source, otherwise the applied voltage has to increase with frequency in order to maintain a constant current.

These remarks led us to consider the configuration illustrated in Fig. 13. The structure consists of a garnet film protected by a SiO_2 layer, then coated with permalloy and electroplated with copper. A periodic pattern could be etched into the conducting materials, making it possible to magnetize the permalloy by launching a current in the copper lines sitting directly on top. Preparations are underway to fabricate such a structure.

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- 7) American Institute of Physics Handbook, McGraw Hill, 3rd ed. (1972) D. E. Gray, ed. 5-105.

FINANCIAL STATEMENT

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<u>Total Amount Contract</u>	<u>Inception to Date</u>	<u>Unexpended Funds</u>
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<u>Required Level of Effort</u>	<u>Inception to Date</u>
1,950 hrs.	1,409 hrs.

APPENDIX

The input impedance of the resonant circuit shown in Fig. 9 is given by:

$$Z_{in} = \frac{j(L + L_s) \omega + R_s}{1 - (L + L_s) C \omega^2 + j R_s C \omega} \quad (A1)$$

For impedance matching, Z_{in} has to be equal to the output-impedance R_o of the power source:

$$Z_{in} = R_o \quad (A2)$$

Equating (A1) and A2) one obtains:

$$j(L + L_s) \omega + R_s = [1 - (L + L_s) C \omega^2] R_o + j R_s R_o C \omega \quad (A3)$$

where the real and imaginary parts are separated:

$$1 - (L + L_s) C \omega^2 = R_s / R_o \quad (A4)$$

$$(L + L_s) / C = R_o R_s \quad (A5)$$

In our case, $R_s / R_o \ll 1$, and Eq. (A4) reduces to the conventional resonance equation $(L + L_s) C \omega^2 \approx 1$. At resonance, Eq. (A1) becomes:

$$Z_{in} \approx (L + L_s) / R_s C$$

which has to be equal to R_o . Thus Eq. (A5) can be viewed as the impedance matching condition.

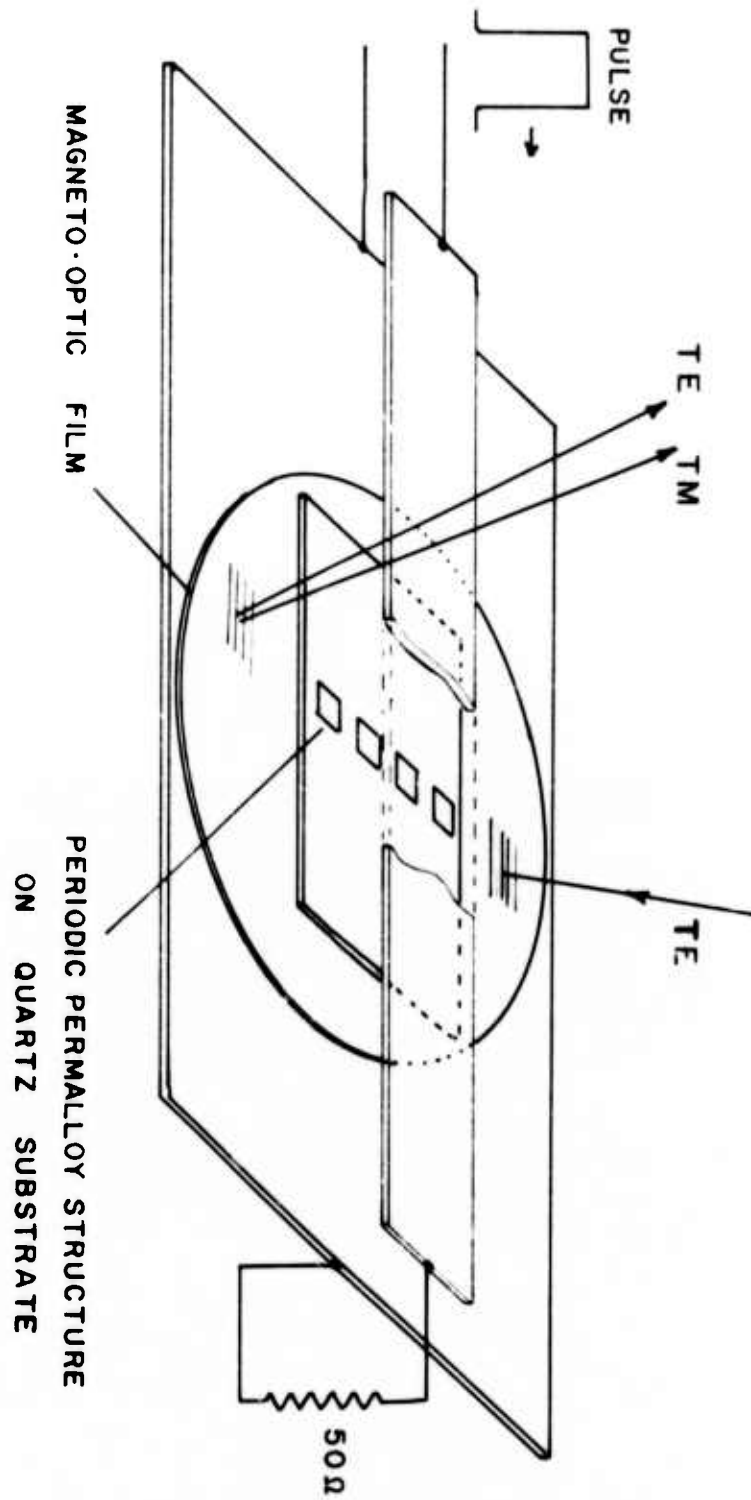


Fig. 1: Experimental configuration used in the pulsed experiment.
The sample and the periodic permalloy structure are both
located in a 50-ohm strip line terminated by a matching load.

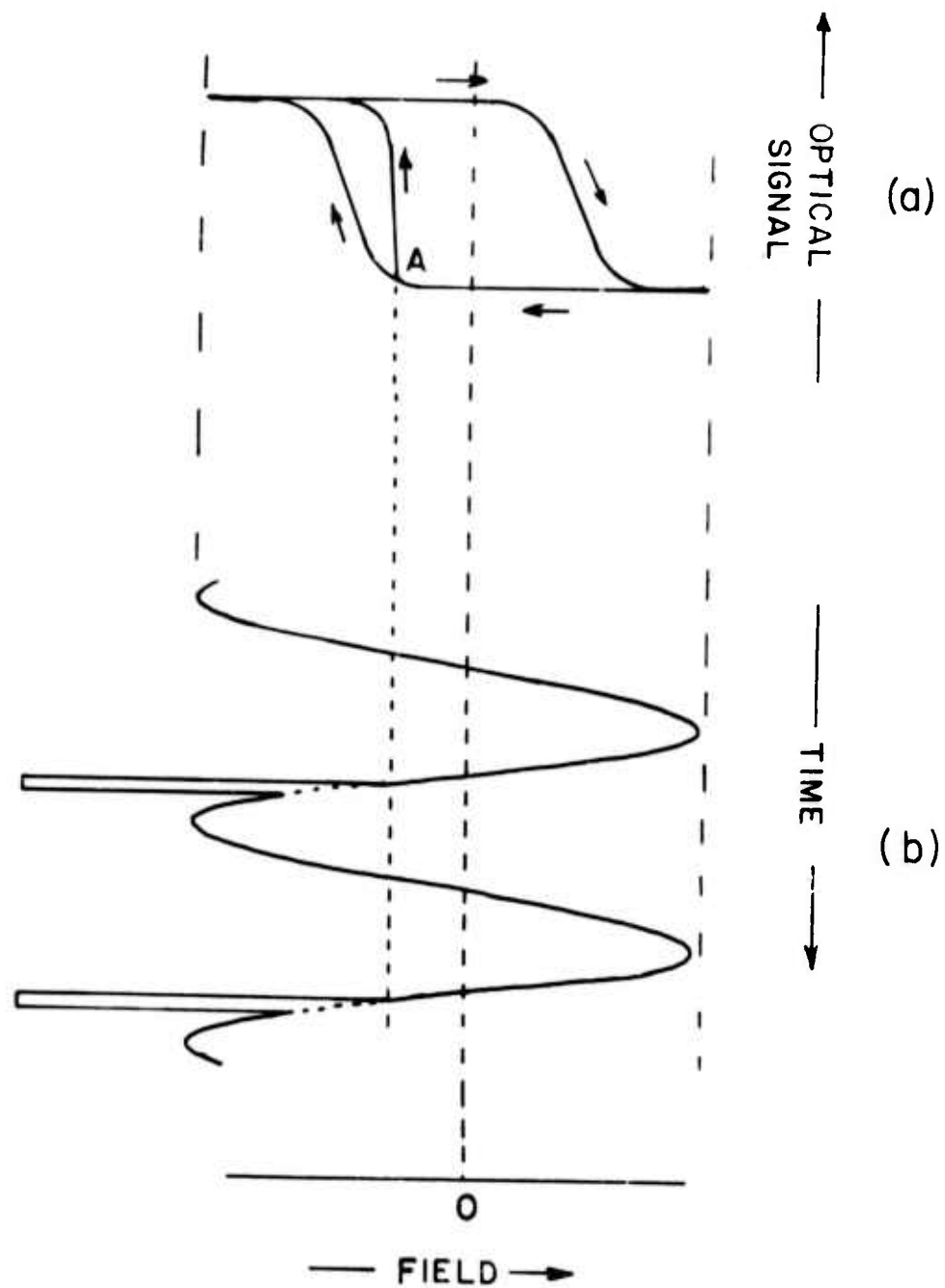


Fig. 2: The pulse, superposed to the external ac magnetic field, is synchronized with the onset of the optical transition which is accelerated.

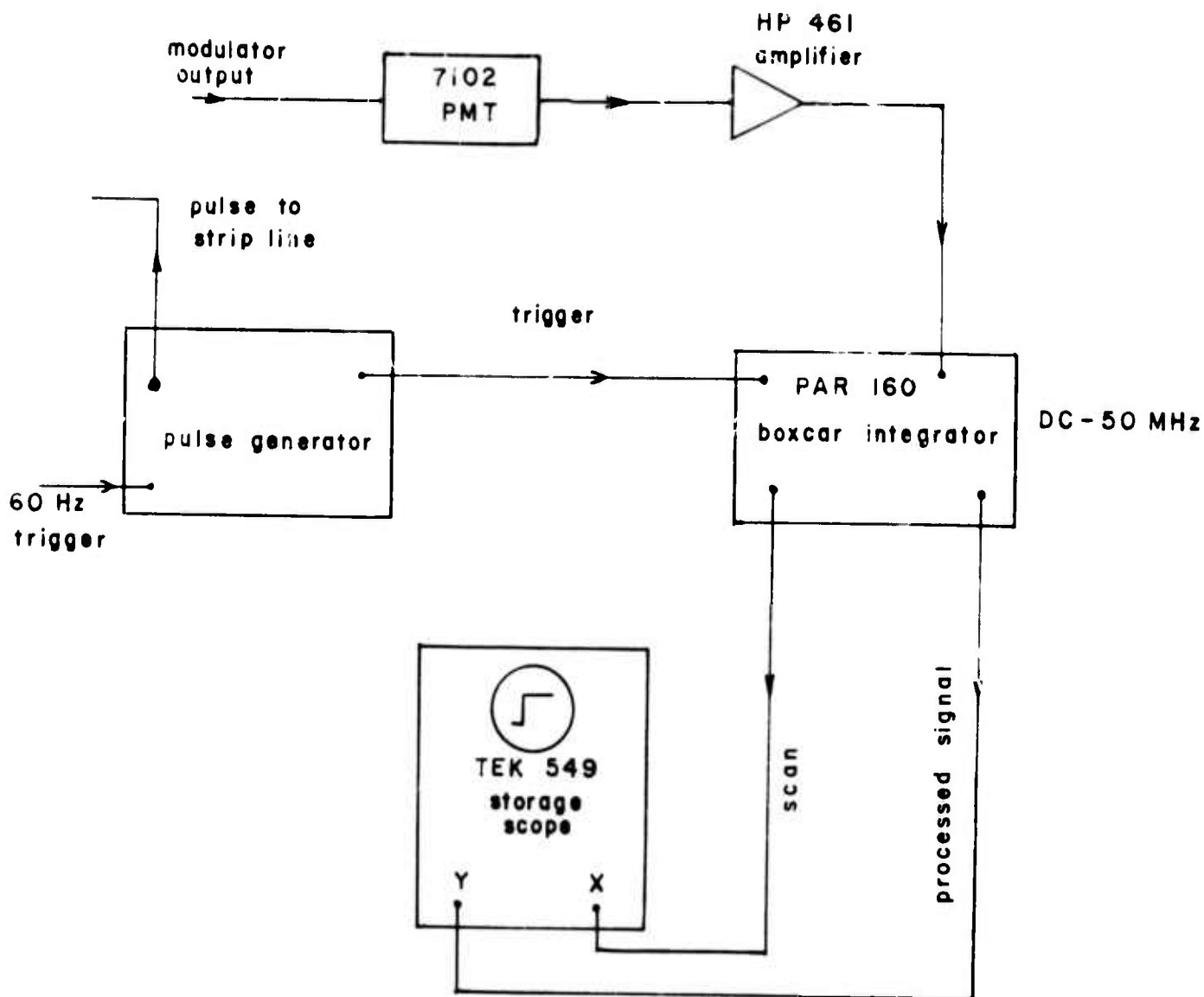


Fig. 3: Schematic of the detection system used in the pulsed experiment.

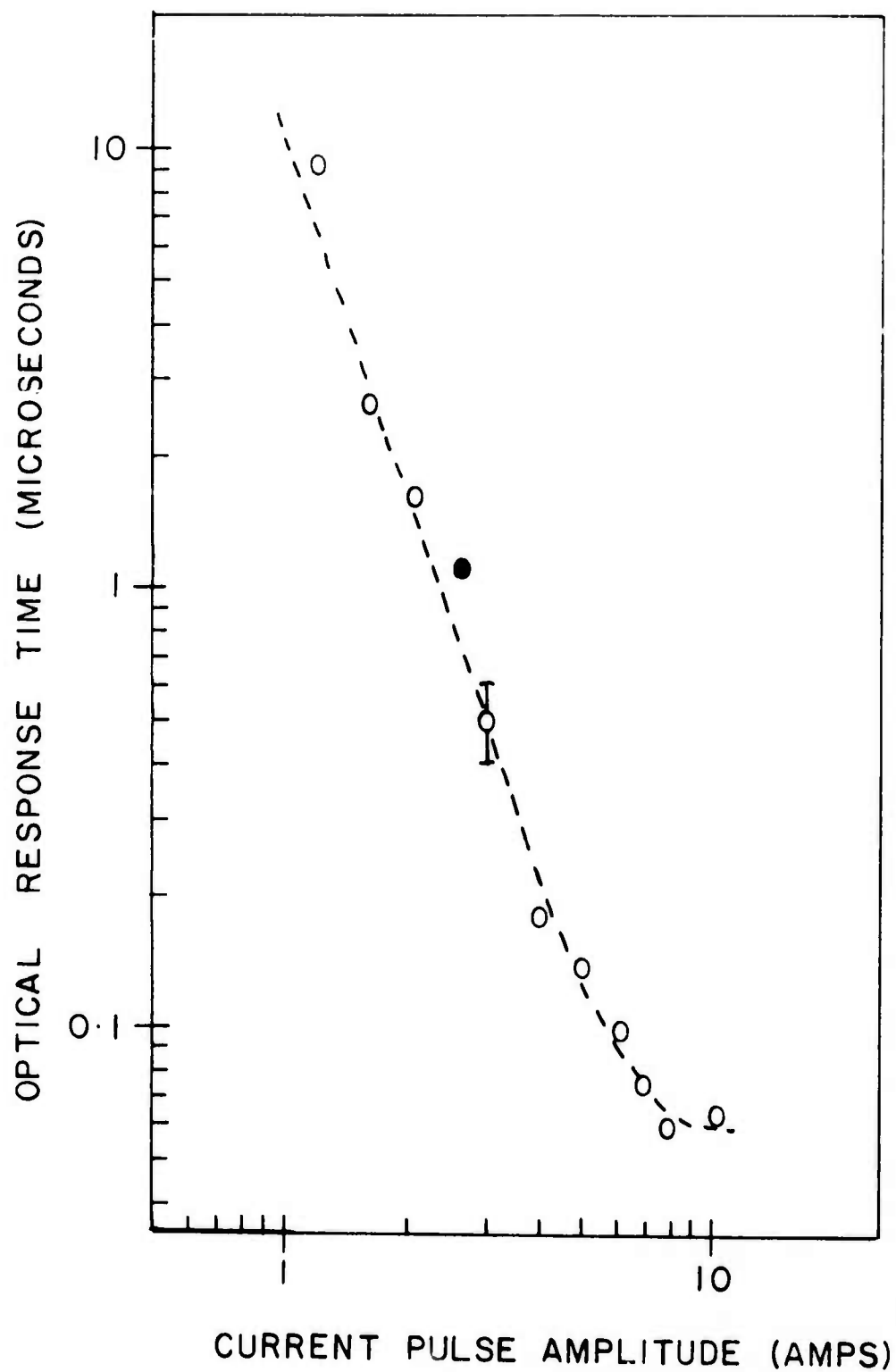


Fig. 4: Rise time of the optical response vs. current pulse amplitude.

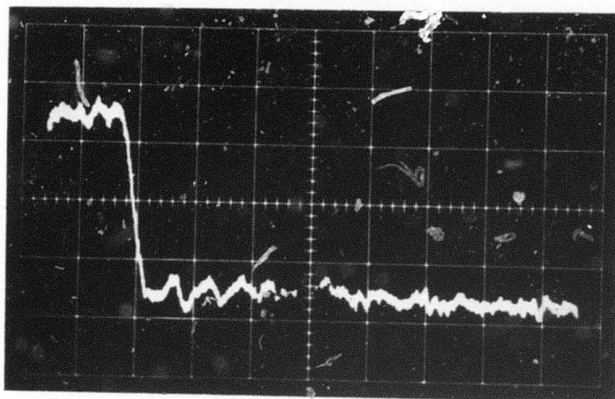


Fig. 5: Optical response (depletion of the TE mode) obtained with a current pulse of 8 Amps. Horizontal scale is 200 nsec/cm. Notice the ringing at the trailing edge of the signal.

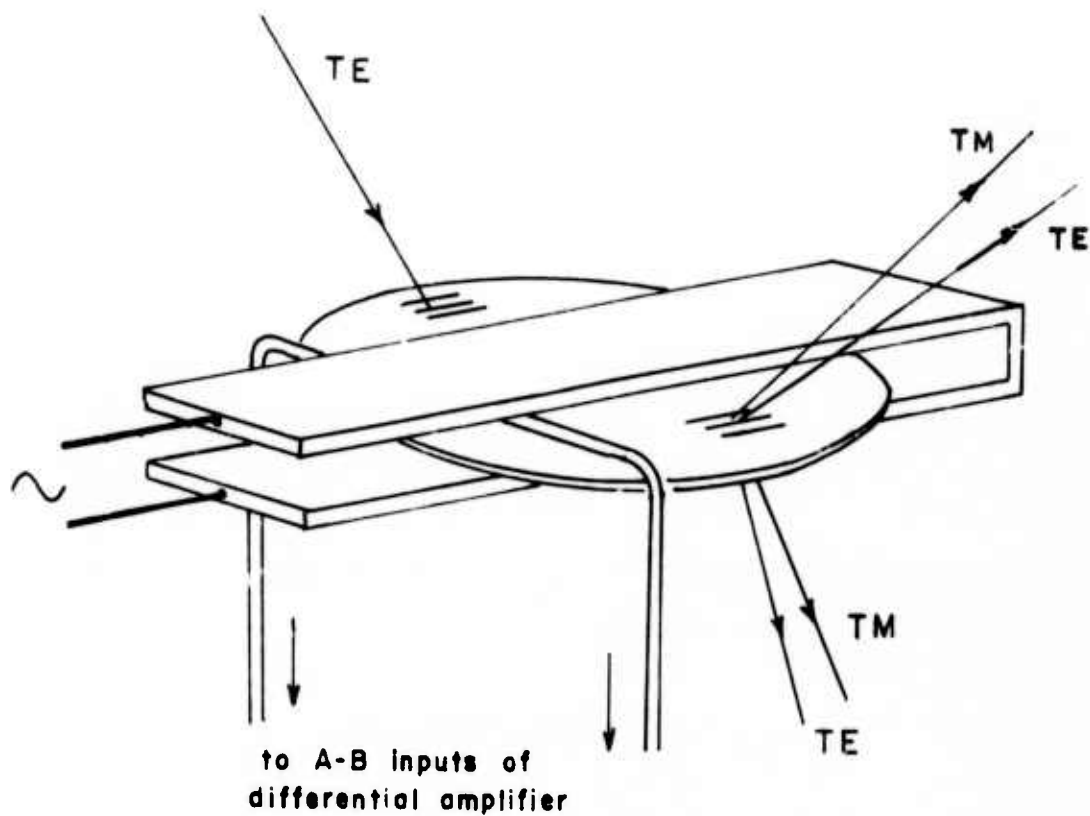
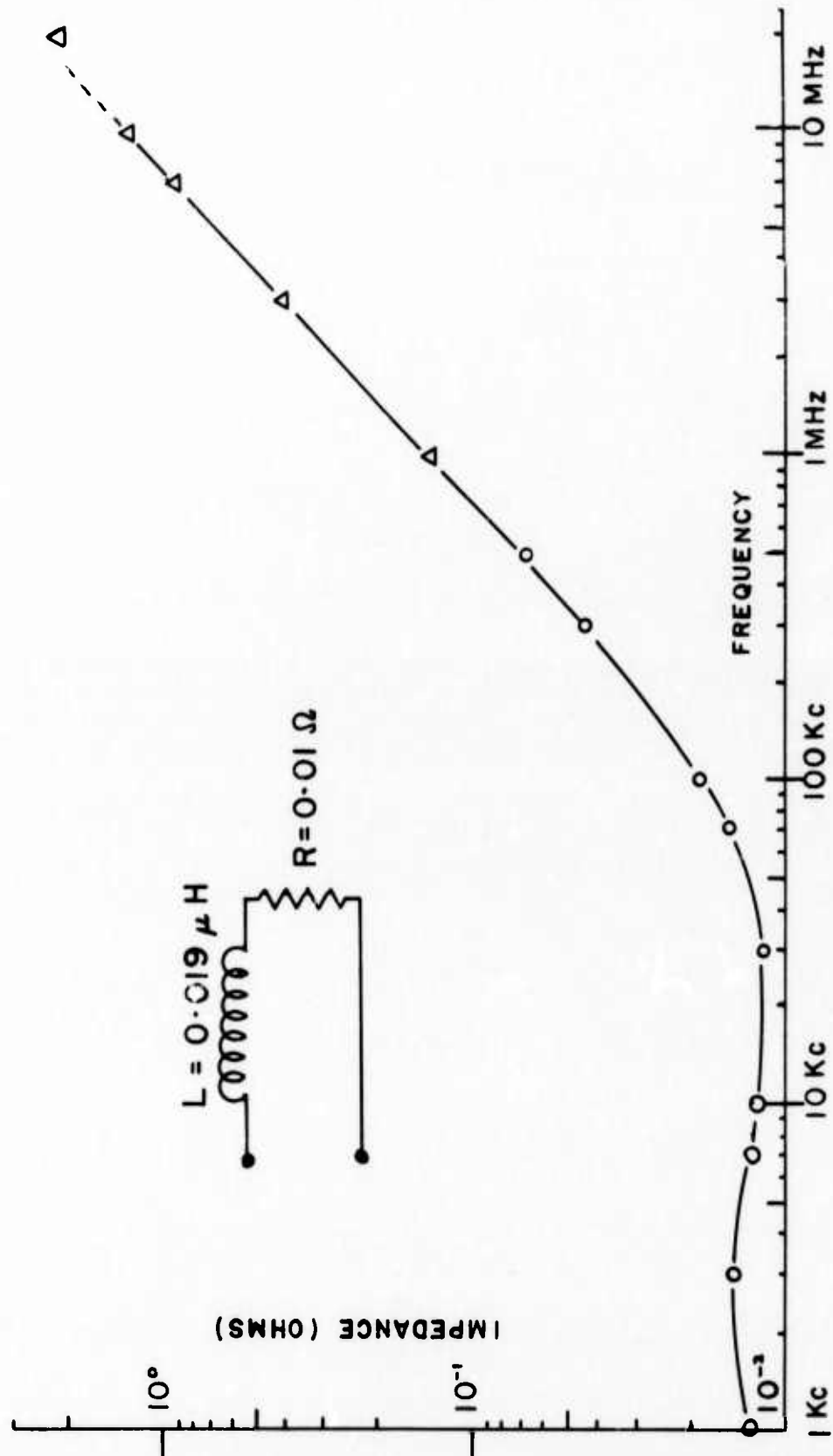


Fig. 6: Experimental configuration used with rf excitation. The magneto-optic sample alone, without any periodic permalloy structure, is placed in a shorted strip line. The half-turn pick-up loop enables simultaneous electro-magnetic sensing.

Fig. 7: Impedance of the shorted strip line as viewed from the generator vs. frequency. Circles and triangles correspond to two different generators. The equivalent circuit shown in the inset is a good approximation of the strip line over the range of frequency shown.



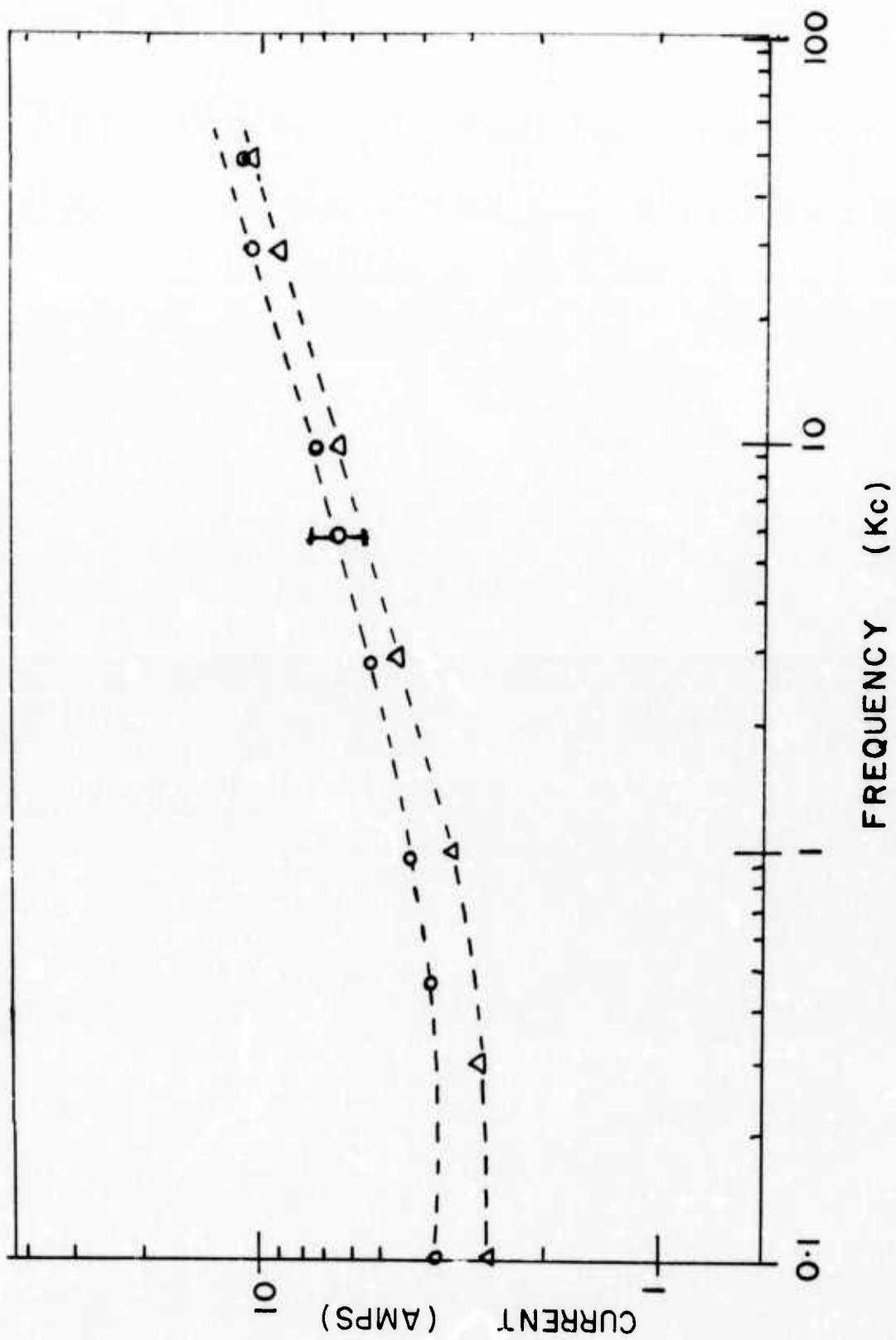


Fig. 8: ac current necessary to reverse the in-plane magnetization in two typical samples as a function of frequency.

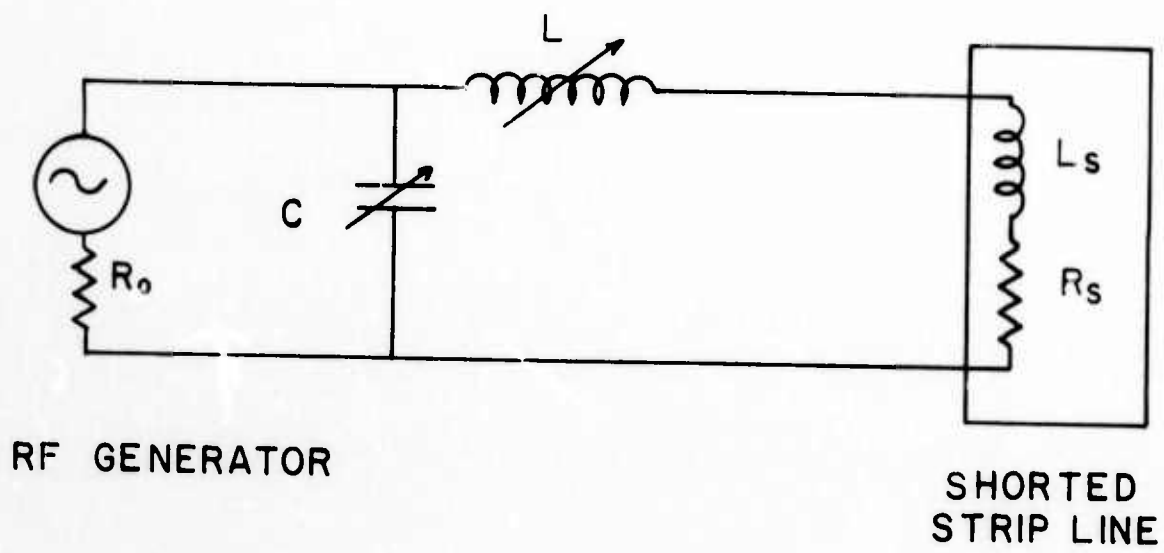


Fig. 9: Simple LC network used to match the shorted strip line to the output impedance of the rf generator.

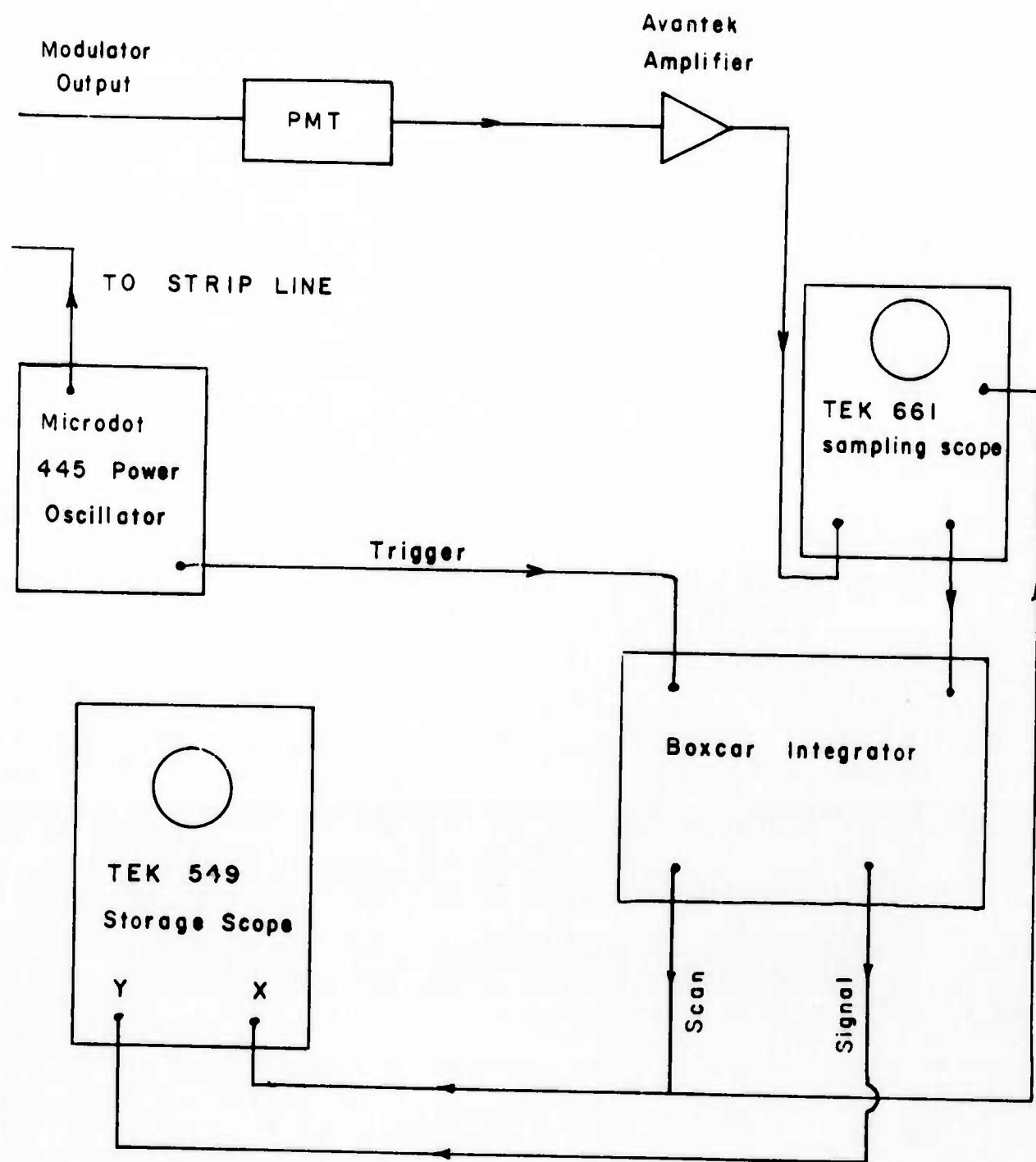


Fig. 10: Detection system used with rf excitation.

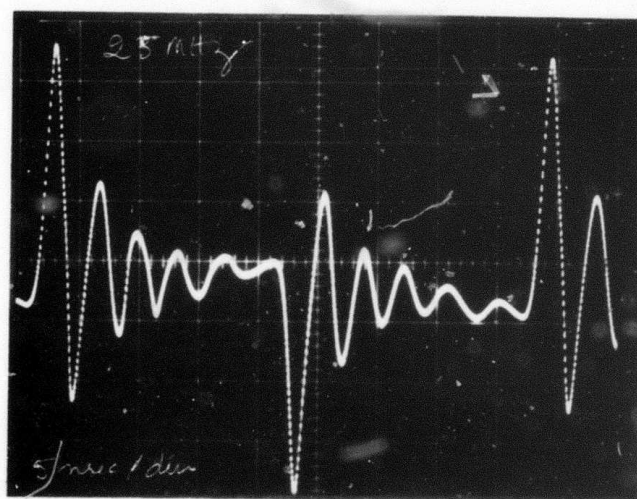
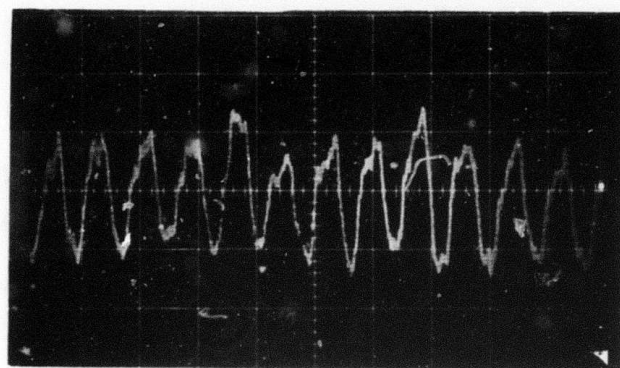


Fig. 11: Top photograph shows optical modulation at 25 MHz. Horizontal scale is 50 nsec/cm. Bottom photograph is a simultaneous picture of the output of the pick-up loop. Notice the under-damped high frequency oscillations. Horizontal scale is 5 nsec/cm.

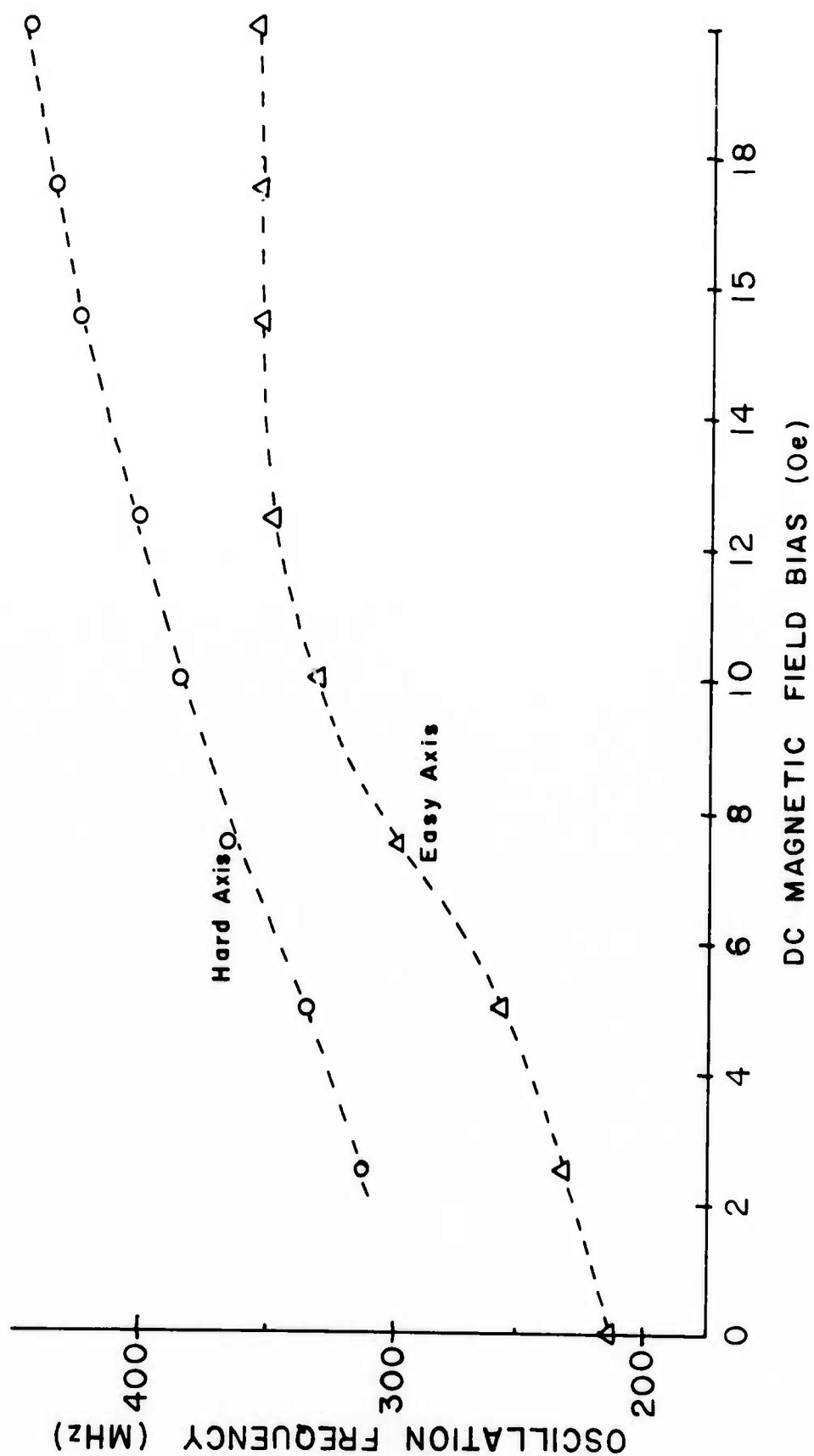


Fig. 12: Natural oscillation frequency of sample #851 vs. perpendicular in-plane dc magnetic field. The rf field is applied along the easy and hard axis, respectively.

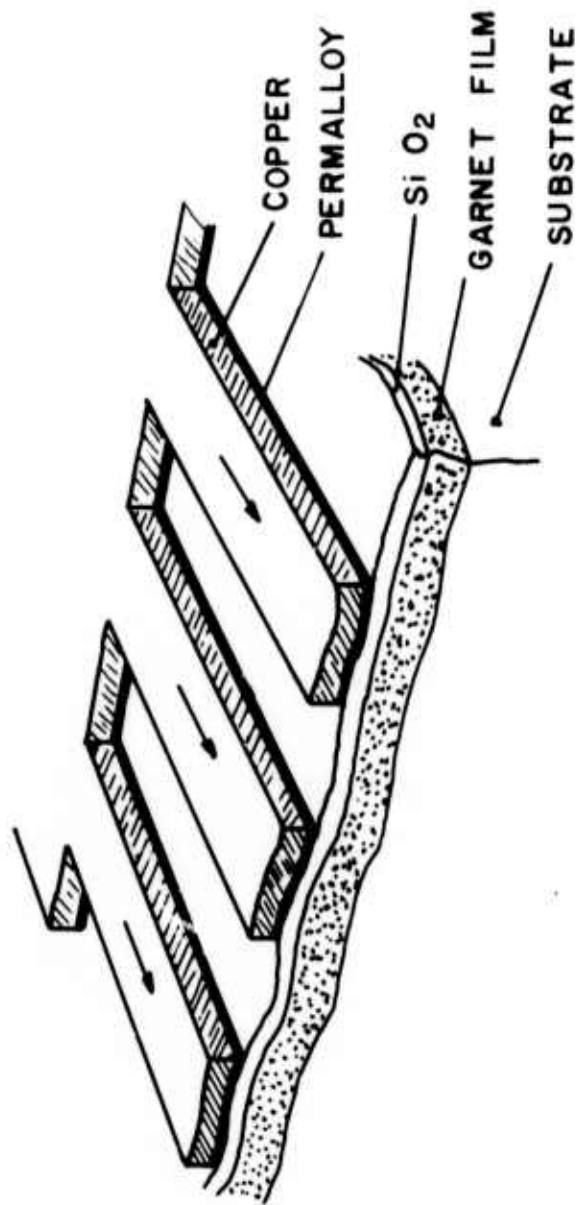


Fig. 13: Proposed configuration for reduced current requirement and improved ruggedness.